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Autophagous Design and Material Options for Forward Deployed Aircraft IR Decoys with Reduced Risk of Foreign Object Damage

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14. ABSTRACT New infrared (IR) decoys are being developed that will be forward launched from a moving aircraft. Autophagous (self-consuming) materials and components that quickly combust after deployment into harmless debris are considered in this study. The possibility of engine ingestion of an intact IR Decoy strongly suggests the use of relatively "soft" materials that will minimize damage. Based on this and other findings determined in this study, a laminate shell design comprised principally of polymeric and organic (e.g., paper) layers joined or embedded with pyrotechnic substances is recommended for further research and development. Such a shell will probably require one or more layers of aluminum foil for oxygen and moisture barrier purposes and an inertia or electric activated primer system for ignition after launch. Properly designed, such an autophagous shell should be capable of providing: (a) protective and safe packaging for the IR Decoy during handling and launch; (b) sustained IR reactivity through protection from the atmosphere; and (c) disintegration via combustion of fragmented pieces prior to possible interaction with the launching aircraft.					
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AUTOPHAGOUS DESIGN AND MATERIAL OPTIONS FOR FORWARD DEPLOYED AIRCRAFT IR DECOYS WITH REDUCED RISK OF FOREIGN OBJECT DAMAGE

INTRODUCTION

New infrared (IR) decoys are being developed that will be forward launched from a moving aircraft. The decoy materials/components pose a threat of foreign object damage (FOD) to the aircraft or its engines after deployment. One-way of avoiding this possibility is to develop autophagous (self-consuming) materials and components for the IR Decoy that quickly transform (via combustion) after deployment into FOD-less debris.

In the course of this study, many possible materials were found that offer the potential for autophagous shell applications. The possibility of ingestion of an intact IR Decoy by an aircraft turbine engine strongly suggests the use of relatively "soft" materials that will minimize damage to the engine hardware. Based on this and other findings determined in this study, *a laminate shell design comprised of principally of polymeric and organic (e.g., paper) layers joined or embedded with pyrotechnic substances* is recommended for further research and development focus. Such a shell will probably require *one or more layers of aluminum foil for oxygen and moisture barrier purposes*, and an *inertia or electric activated primer system* for ignition after launch. Properly designed, such an autophagous shell should be capable of providing: a.) protective and safe packaging for the IR Decoy during handling and launch; b.) sustained IR reactivity through protection from the atmosphere; and c.) disintegration via combustion of fragmented pieces prior to possible interaction with the launching aircraft.

This report contains four main sections: Design/Operational Requirements, Materials Survey, Preliminary Design Concepts, and Recommendations.

DESIGN/OPERATIONAL REQUIREMENTS

The shell for the IR Decoy must serve as an airtight container for the chaff that is capable of withstanding all storage and handling loads prior to launch. Appropriate standards governing the storage and handling performance of aircraft munitions (storage times, temperatures, and environments, handling and drop loads, crush strengths, etc.) will need to be considered in the design and selection of materials for the shell.

The IR chaff reacts with oxygen in air to produce its thermal signature. This means that the chaff will have to be isolated from ambient air and moisture prior to launching and then exposed and dispersed while in flight after launching. This implies the need for an air/moisture "barrier layer" container for the chaff. Some sort of "exposure" indicator on the shell is highly desirable. The best performing materials for gas/moisture barrier layers are polymer laminates with at least one layer of aluminum foil. Many commercial products of this type are available; it is commonly used for packaging lithium-ion batteries.

The decoy shell will have to withstand the launch loads, deliver the chaff some distance in front of the aircraft, disgorge and/or disperse the chaff, and then transform into harmless debris before the aircraft can reach the shell. The allotted time for chaff delivery, dispersion, and the transformation of the shell and auxiliary hardware into harmless debris is on the order of a few seconds, and the decoy shell will have to initiate these events at precise times after launch. The ability to adjust the delay times just prior to use would be another useful feature to consider.

The largest mechanical loads in the decoy shell will arise during launch from the moving aircraft. An electromagnetic rail gun is currently being considered for launching the decoy. The decoy and rail gun specifications listed in Table 1 have been supplied by TEW. The parameters listed in Table 2 are calculated using standard physics formulas (e.g., 1-D constant acceleration dynamics) with the specified parameter values given in Table 1.

Parameter	Current Design Value
Ejection Velocity	140 m/sec
Total Decoy Mass	340 g
Decoy Length and Diameter	16.5 cm (6.5 in) and 3.46 cm (1.363 in)
Rail Gun Length	0.864 m (34 in)
Rail Gun Bore	Square: 4.45 cm (1.75 in)
Chaff Volume	43.8 cm ³
Chaff Length and Diameter	5.54 cm (2.180 in) and 3.18 cm (1.25)
Decoy-to-Aircraft Intersect Time	~3.2 sec

Table 1: IR Decoy and Rail Gun (Fully-Augmented) Specifications

Parameter	Calculated Value
Ejection Acceleration	11,348 m/s ² or 1157g
Total Time in Rail Gun	12.3 msec
Kinetic Energy of Decoy at Launch	3332 J
Axial Launch Load	3860 N

Table 2: IR Decoy Load and Dynamics Specifications

The decoy shell will have to withstand large loads imposed during launching. Large mechanical deformations, tube buckling, or premature fracture can adversely affect the flight characteristics of the shell. The loads are primarily compressive, in nature, arising during acceleration of the decoy within the EM rail gun. The magnitude of the acceleration loads is directly proportional to the total projectile mass. Compressive loading can lead to shell failure via yielding of the shell material or buckling instability of the shell. These facts will be important to keep in mind during the design and sizing of the shell.

One critical requirement on the decoy shell and hardware and the reason why this study was commissioned is the need for complete transformation of the materials into "harmless (FOD-less; Foreign Object Damage-less) debris" prior to possible contact with the aircraft. That is, the IR Decoy should not be capable of causing significant damage to the exterior of the aircraft or to the gas turbine engines if ingested. There are a number of existing FOD standards for ingestion of various types of debris (e.g., hailstones, birds, cleaning grit, etc.), but clearly, the only innocuous debris is no debris!

I spoke with two individuals concerning FOD: Dan Popgoshev at the Naval Pax River facility (301-757-0453), and Jennifer Bradley at Honeywell Corp. in Phoenix Arizona (602-231-2417). Dan Popgoshev said that decoy launch and flight characteristics and aircraft trajectories after launch will have to be carefully designed during advanced development of the IR Decoy. He implied that the IR Decoy system should be specifically designed to avoid any possibility of contact with the aircraft during and after launch. Assuming the operational objectives of the decoy can still be satisfied, this would greatly decrease the possibility of FOD.

Jennifer Bradley has been involved in FOD testing on gas turbine engines for aircraft propulsion at Honeywell Corp. She related her experiences on the ingestion of hailstones, ice slabs, birds, and in one case, an air turbine starter hose (~2 ft length, rubber layers with braided wire mesh). Hailstones, ice, and birds don't typically damage the engine, but significant internal damage was noted in the engine components after accidental ingestion of the turbine starter hose. She also noted that FOD can often times be detected while in flight by large engine vibrations.

MATERIALS SURVEY

The operational requirements of the IR Decoy imply that candidate autophagous shell design/materials must be capable of achieving the following basic performance objectives:

- Provide O₂ and moisture protection for the IR chaff prior to launch.
- Contain the chaff and maintain aerodynamic form before, during, and after launch.
- Discharge and disperse the chaff at the appropriate moment after launch.
- Transform into FOD-less debris after chaff discharge via combustion with a thermal signature that is compatible with that of the chaff materials.

Most solid materials can be rapidly transformed, under the proper conditions, into microscopic size particles and gases through a combustion process (i.e., catalytic exothermic oxidation reaction). Combustion of a solid in air involves a number of coupled processes (Figures 1-3). Namely, vaporization of the solid (pyrolysis) into gaseous fuel, mixing with air (oxidizer), and then flame burning of the gaseous fuel/oxidizer mixture. Pyrolysis of the solid requires an input of energy that is typically supplied, after ignition, by the heat generated during combustion of the gaseous mixture. The key to developing a self-catalyzing combustion (autophagous) process is to properly channel the energy liberated during combustion of the gaseous fuel/oxidizer for further pyrolysis of the solid. That is, proper design of the “thermal feedback process” (see Figure 1) in the operational autophagous system. This assumes that the energy liberated during combustion (Q₂) is greater than that required for pyrolysis (Q₁), which is true for polymers and other natural organic materials.

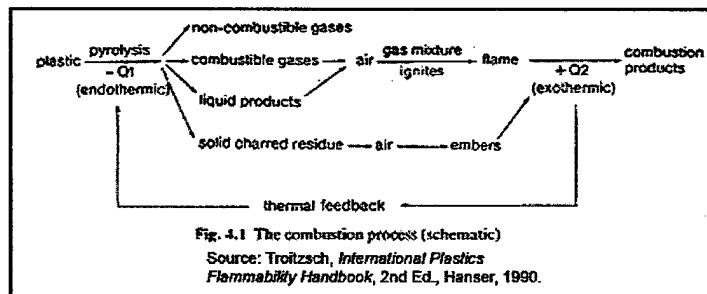


Figure 1: Physical processes involved in the combustion of solid materials, polymers in particular (from [1]).

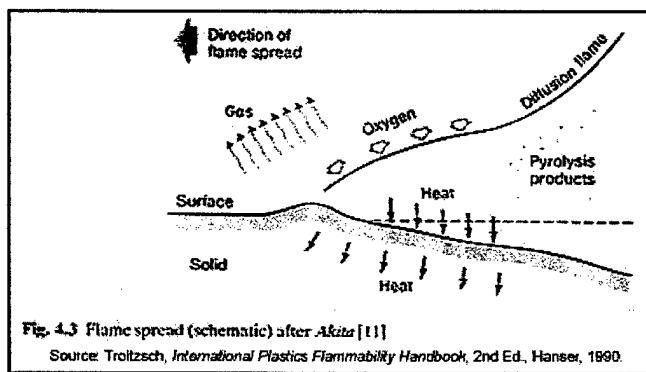


Figure 2: Flame spread on a material surface (from [1]).

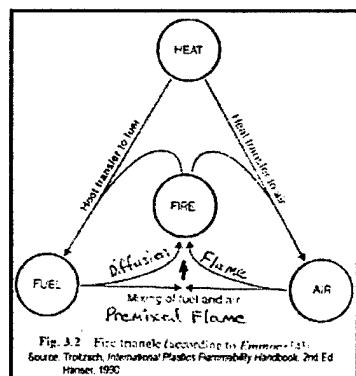


Figure 3: The three ingredients (fuel, air, heat) and their coupling for combustion (fire) of solids (from [1]).

The temperatures that develop during combustion of a solid can vary considerably depending on the material being burned and the nature of the “thermal-combustion system.” In general, the temperature of burning for materials can be ranked in the following order¹:

Hottest: refractories/oxides & metals → polymers → natural organics :Coolest

Many refractories and oxides will not burn with air as the oxidizer. They may instead react, change phase, or sublime at high temperatures. Several metals are commonly used in pyrotechnic and thermite welding applications [7] including: aluminum, magnesium, titanium, iron, and zirconium. A detailed model for the combustion of metals in air can found in [28].

Polymers and other organic substances are generally combustible in air. A significant area of research is devoted to understanding the “flammability of polymers” with the goal of minimizing damage to life and property during accidental fires. A number of flammability references are listed [1-6]; several Figures and Tables from the book by Troitzsch [1] are included in this report.

Fire² [2] has classified groups of plastics by their chemical composition. Polymers containing only carbon and hydrogen are known as the **hydrocarbon plastics** and include: polypropylene, polyethylene, polystyrene, polybutadiene, and polybutylene. These plastics burn faster and hotter than other plastics since their polymer chains are all fuel, and they burn cleaner since all of the potential intermediate chains are combustible [2]. Slower burning types of polymers include those containing: C, H, and O; C, H, and N; and C, H, and a halogen.

Quantifying the flammability of a material is complex and depends on a number of factors. **Heat release rate (HRR)**, an experimentally determined parameter, is a good indicator of the fire hazard of a material in forced flaming combustion [29]. Walters and Lyons [29] advocate the use instead of **heat release capacity (HRC)**, defined as the HRR divided by the rate of temperature rise, because it is proportional to the HRR and can be easily calculated using independent chemical structure data for the polymer. Figure 4 shows the HRR versus HRC for

¹ Compare the melting or boiling temperatures (are assumed to be significantly higher than the melting or boiling points when combustion is possible) for refractory and oxide materials [1; Tables 18 & 16] and metals [1, Table 15] (e.g., Ti:3260 °C ; Fe:2800 °C ; Al:2327 °C ; Mg:1120 °C ; Zn:907 °C) with the decomposition, flash, or self-ignition temperatures shown for select polymers in Figure 5.

² What are the chances that a man named Fire would end-up doing “flammability” research?

constant heat input (50 kW/m^2) demonstrating proportionality. In this study, the plot is most useful for graphically illustrating the flammability of various thermoplastic and thermosetting polymers. Flammability is indicated by distance from the graph origin. The plot shows the relatively higher "flammability" of the hydrocarbon polymers (PP, PE, and PS). A compilation of HRR, HRC, and %Char (charring) values for a number of thermoplastic and thermosetting polymers can be found in Table 1 of [29].

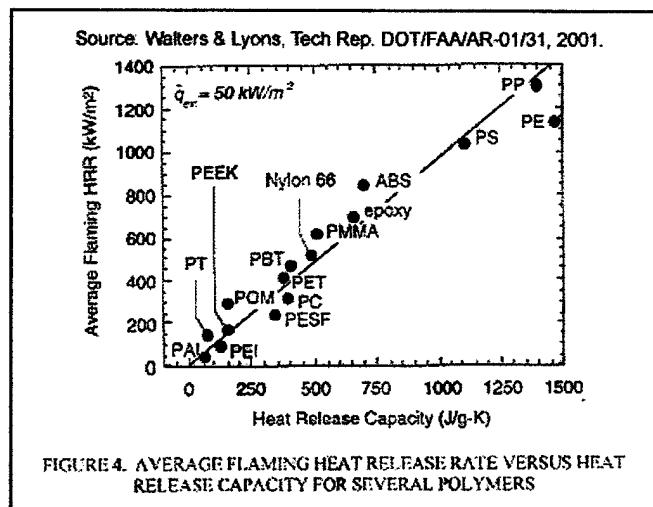


Figure 4: Heat release rate versus heat release capacity (from [29]). Flammability is related to distance from the graph origin. Polyethylene, polypropylene and polystyrene have the highest flammability.

Several combustion properties for thermoplastics are listed in Figure 5 below. Included are decomposition and ignition temperatures, heats of combustion, etc. Additional information can be found in references [1-7].

A review of US patent literature uncovered relevant technology under the guise of combustible shells, cartridges, or cases [8-27] (cover sheets included in the Appendix). Numerous designs are described for shells and casings that combust on or after firing leaving little or no residue. The ones particularly relevant to this work are briefly described below. US Patent #3,977,325 [27] describes a combustible shell made from nitrated textile threads wound on a mandrel with a polymer outer coating for handling and environment protection. Mention is made of co-spinning of polymer and nitrated textile threads to achieve combustible fibers of significant strength. US Patent #4,119,036 [25] describes combustible rocket motor cases made of a laminate of metal foils (e.g., Al, Mg, Ti, steel) and polymer sheets bonded with a combustible epoxy adhesive containing oxidizing agents and combustion controlling additives. US Patent #4,649,827 [21] describes the use of combustible paper tapes (soaked in nitrocellulose) for helically wound cylindrical shells. US Patent #5,526,750 [11] describes combustible shells for fireworks comprised of nitrocellulose with a polymer binder. The shell burn rate is enhanced by coating the inside of the shell with a primer compound (e.g., black powder), and grooves or ridges are added to the inner surface to facilitate fracture of the shell into smaller pieces. Also discussed is an interesting air-pressure launcher for the shell that allows for very precise control over the shell trajectory.

In related patents, US Patent #4,532,866 [22] describes an impact/friction activated safety primer with a very selective percussion range. US Patent #5,052,302 [15] describes an unpressurized combustible primer for cannon cartridges. The primer uses a very interesting “igniter strand” comprised of nitrocellulose sheathed in a polypropylene jacket. This strand is supposedly available commercially. Ignition flame speeds of 1300 to 1500 m/s are possible if the strand is radially confined for the first ~1.4 inches of burn. Additional references related to devices/systems for activation include [30-31].

A very interesting book and an excellent source of information on pyrotechnic materials is “Military and Civilian Pyrotechnics” by Ellern [7]. He reviews the science of pyrotechnics for heat generation, safety matches, flares, smoke, sound, flame, etc., presenting a very broad and readable overview on the subject. Recipes for a variety of pyrotechnic formulations are included.

Table 4.1 Range of decomposition of some plastics [1]

Plastic	T _d [°C]	Plastic/natural product	T _d [°C]
Polyethylene	340–440	Polymethyl methacrylate	180–280
Polypropylene	320–400	Polyacrylonitrile	250–300
Polystyrene	300–400	Polyamide 6	300–350
Polyvinyl chloride	200–300	Polyamide 66	320–400
Polytetrafluoroethylene	500–550	Cellulose	280–380

Table 4.2 Flash-ignition and self-ignition temperatures of various plastics by ASTM D 1929

Plastic/natural product	FT* [°C]	SIT** [°C]
Polyethylene	340	350
Polypropylene	320	350
Polystyrene	350	490
Polyvinyl chloride	390	450
Polytetrafluoroethylene	560	580
ABS	390	480
Polymethyl methacrylate	300	430
Polyacrylonitrile	480	560
Polyamide 6	420	450
Polyamide 66	490	530
Polyurethane (rigid foam)	310	415
Cotton	210	400 ← Cellulose

* FT = Flash-ignition temperature

** SIT = Self-ignition temperature

Table 4.3 Heats of combustion of various plastics and natural products [12]

Plastic	ΔH [kJ·g ⁻¹]	Plastic/natural product	ΔH [kJ·kg ⁻¹]
Polyethylene	46 500	Polyamide (6 or 66)	32 000
Polypropylene	46 000	Polyester resin	18 000
Polyisobutylene	47 000	Natural rubber	45 000
Polystyrene	42 000	Cotton	17 000
ABS	36 000	Cellulose	17 500
Polyvinyl chloride	20 000	Celluloid	17 500
Polymethyl methacrylate	26 000		

Table 4.4 Thermal characteristics of various thermoplastics

Polymer	Bulk density		Temperature resistance		Vicat-softening point B [°C]	Decomposition range [°C]	Flash-ignition temperature* [°C]	Self-ignition temperature ^a [°C]	Heat of combustion ΔH [kJ·kg ⁻¹]
	[g/cm ³]	short term [°C]	long term [°C]	[°C]					
Polyethylene LD ^b	0.91	100	80	—	340–440	340	350	46 600	
HD	0.96	125	100	75	—	—	—	—	
Polypropylene	0.91	140	100	145	330–410	350–370	390–410	46 000	
Polystyrene	1.05	90	80	88	300–400	345–360	490	42 000	
ABS	1.06	95	80	110	—	390	480	36 000	
SAN	1.08	95	85	100	—	370	455	—	
PVC rigid	1.40	75	60	70–80	200–300	390	455	20 000	
Polyvinylidene chloride	1.87	150	—	—	225–275	>530	>530	10 000	
Polytetrafluoroethylene	2.20	300	260	—	510–540	560	580	4 500	
Poly methyl methacrylate	1.18	95	70	85–110	170–300	300	450	26 000	
Polyamide 6	1.13	150	80–120	200	300–350	420	450	32 000	
Polyethylene terephthalate	1.34	150	130	80	285–305	440	480	21 500	
Poly carbonate	1.20	140	100	150–155	350–400	520	— ^c	31 000	
Polyoxymethylene	1.42	140	80–100	170	220	350–400	ca. 400	17 000	

^b LD = Low density^c HD = High density^a no ignition^c by ASTM D 1929Source: Troitzsch, *International Plastics Flammability Handbook*, 2nd Ed., Hanser, 1990.

Figure 5: Several tables with experimental data related to the combustion of polymers (from [1]).

PRELIMINARY DESIGN CONCEPTS

As mentioned previously, there are several design/material constraints and objectives that must be met by an autophagous shell design for the IR Decoy. These include:

- Provide O₂ and moisture protection for the IR chaff prior to launch.
- Contain the chaff and maintain aerodynamic form before, during, and after launch.
- Discharge and disperse the chaff at the appropriate moment after launch.
- Transform into FOD-less debris after chaff discharge.

Another potential constraint is that accidental ingestion of an intact IR Decoy (shell, chaff, and armature) will cause no damage to the engine. It seems that the only way this can be achieved is to eliminate or minimize the use of metal and ceramic components in the decoy. The O₂-moisture barrier-layer and the current-carrying armature functions will require metallic components. Aluminum foil (thin) can be used for an O₂-moisture barrier-layer, and pure aluminum wires, which are very soft and ductile, can be used for the EM gun current armature. The remaining shell components can be constructed using polymers and papers configured in laminate form for mechanical stiffness and strength. These components should be relatively harmless if accidentally ingested.

An aluminum O₂-moisture barrier-layer will be required if medium to long-term shelf-life is to be achieved with the IR Decoy [32,33,31]. The Al layer does not have to be thick, just contiguous, and it is probably soft enough to avoid significant damage to the engine upon accidental ingestion. Aluminum is combustible and is often used in pyrotechnic applications.

The second objective can be achieved through proper selection and design of the shell wall materials for the selected shell geometry. The maintenance of decoy flight (aerodynamic) characteristics depends largely on its ability to maintain its shape during and after launch. This ability is related to the structural performance capabilities of the shell (e.g., stiffness, buckling and yield and fracture strengths, etc.). Prediction and modeling of the mechanical performance is straightforward once the loads, geometry, and materials are specified. Useful references include: Ashby [34] (ranking of materials using performance indices); Roark and Young [35] (shell stress and buckling analysis); Timoshenko and Gere [36] and Gerard [37] (shell buckling analysis).

Poor et al. [11] advocate the use of combustible shells with hemispherical ends and cylindrical bodies. They claim this shape is allows for particularly simple and flexible manufacture and superior flight characteristics (trajectory distance and accuracy of detonation) when compared with that of spherical, cylindrical, and bullet-shape shell geometries.

Discharging the chaff at the appropriate moment after launch will require a fuse mechanism triggered by the launch. An autophagous ignition network can be embedded in the shell to start the shell fracture and combustion process. An inertia-activated trigger is safe and can be used with the “high-g” EM gun launch (see, for example, Linden and Reddy [31]). Delay times for the start of shell combustion and chaff discharge that can be set in the field would be a nice feature that can be easily incorporated with programmable electronic trigger devices [11].

Complete disintegration of the non-IR target components of the decoy can be achieved using a laminate design with polymer/paper layers having embedded pyrotechnic substances and bonded together using pyrotechnic adhesives. Internal grooves or ridges should be added for facilitating fracture into small pieces after launch and autophagous ignition, and cord-like pyrotechnic fibers can be used for reinforcement and the ignition network.

RECOMMENDATIONS

In the course of this study, many possible materials were found that offer the potential for autophagous shell applications. The possibility of ingestion of an intact IR Decoy by an aircraft turbine engine strongly suggests the use of relatively "soft" materials that will minimize damage to the engine hardware.

Based on this and other findings, *a laminate shell design comprised of principally of polymeric and organic (e.g., paper) layers joined or embedded with pyrotechnic substances* is recommended for further research and development focus. Such a shell will probably require *one or more layers of aluminum foil for oxygen and moisture barrier purposes*, and an *inertia or electric activated primer system* for ignition after launch. Properly designed, such an autophagous shell should be capable of providing: a.) protective and safe packaging for the IR Decoy during handling and launch; b.) sustained IR reactivity through protection from the atmosphere; and c.) disintegration via combustion of fragmented pieces prior to possible interaction with the launching aircraft.

Research and development of the *Autophagous IR Decoy Shell* will require expertise in: **pyrotechnics** (materials selection, design, and testing), **combustion** (thermal system design and testing), and **materials/mechanics** (material/structure design, analysis, and testing). An integrated design effort that considers both the pyrotechnic/combustion and mechanical performance aspects is needed. Several individuals and organizations with skills in the different areas are identified below. It is suggested that meetings be scheduled with the individuals below to more fully ascertain their capabilities and interests in participating in this IR Decoy R&D project, assuming the autophagous concept is pursued.

Pyrotechnic Materials, Design and Testing:

NAVSEA Indian Head
Naval Surface Warfare Center Division
POC: Tom Russell, R&D Head
301-744-4323

Combustion and Heat Transfer Design:

Naval Research Laboratory
POC: Doug Ladouceur, Code 6111
202-767-3558

Wind-Tunnel Testing:

NAVSEA Crane
Naval Surface Warfare Center Division
POC: Code 40 Ordnance Engineering Directorate
<http://www.crane.navy.mil/organization/scripts/code40.cfm>

Materials/Mechanical Design, Analysis and Testing:

Multifunctional Materials Branch, Code 6350
Naval Research Laboratory
POC: James Thomas, Code 6353
202-404-8324; jthomas5@anvil.nrl.navy.mil

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ABBREVIATIONS FOR PLASTICS

2 Abbreviations for Plastics

Plastic	Abbreviation	Plastic	Abbreviation
Thermoplastics			
polyethylene	PE	– hexamethylene diamine	
high density polyethylene	PE-HD	and adipic acid	PA 66
low density polyethylene	PE-LD	– laurinolactam	PA 12
polypropylene	PP	polymethyl methacrylate	PMMA
polystyrene	PS	polyethylene terephthalate	PET
styrene butadiene		polybutylene terephthalate	PBT
copolymer	SB	polycarbonate	PC
acrylonitrile butadiene		polyoxymethylene	POM
styrene copolymer	ABS	Thermosets	
acrylonitrile styrene		polyurethane	PUR
acrylic ester copolymer	ASA	polyisocyanurate	PIR
styrene acrylonitrile		phenol formaldehyde resin	PF
copolymer	SAN	urea formaldehyde resin	UF
polyvinyl chloride	PVC	melamine formaldehyde resin	MF
chlorinated polyvinyl chloride	PVCC	epoxy resin	EP
polyvinylidene chloride	PVDC	unsaturated polyester resin	UP
polytetrafluoroethylene	PTFE	High temperature resistant	
perfluoroethylene propylene	FEP	plastics	
ethylene tetrafluoroethylene		polyphenylene ether	PPE
copolymer	ETFE	polyphenylene sulphide	PPS
polyvinyl fluoride	PVF	polyether sulphone	PES
polyvinylidene fluoride	PVDF	polysulphone	PSO
polychlorotrifluoroethylene	PCTFE	polyimide	PI
polyamide	PA	polybenzimidazole	PBI
based on			
– ϵ -caprolactam	PA 6		

Source: Appendix 2 of Troitzsch [1].